NLO QCD corrections to $Wb\bar{b}/Zb\bar{b}$ production at hadron colliders

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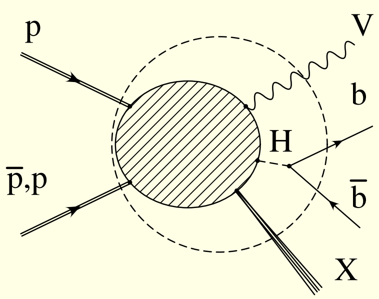
RADCOR 07, Florence, October 2007

- Motivations: $Wb\bar{b}/Zb\bar{b}$ main background to
  - $\rightarrow$ WH/ZH associated production;
  - $\rightarrow$ single-top production.
- $Wb\bar{b}/Zb\bar{b}$ NLO QCD calculation, b massive.
- Numerical results: inclusive/exclusive cross-sections (Tevatron).
- Summary and outlook.

In collaboration with F. Febres Cordero and D. Wackeroth

Motivations

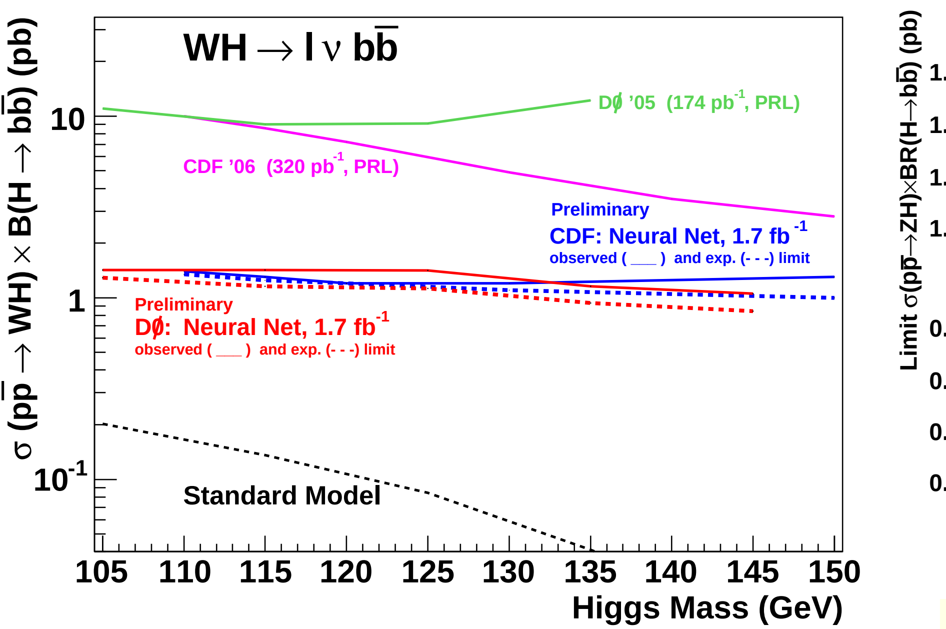
Associated production of SM Higgs with weak vector bosons



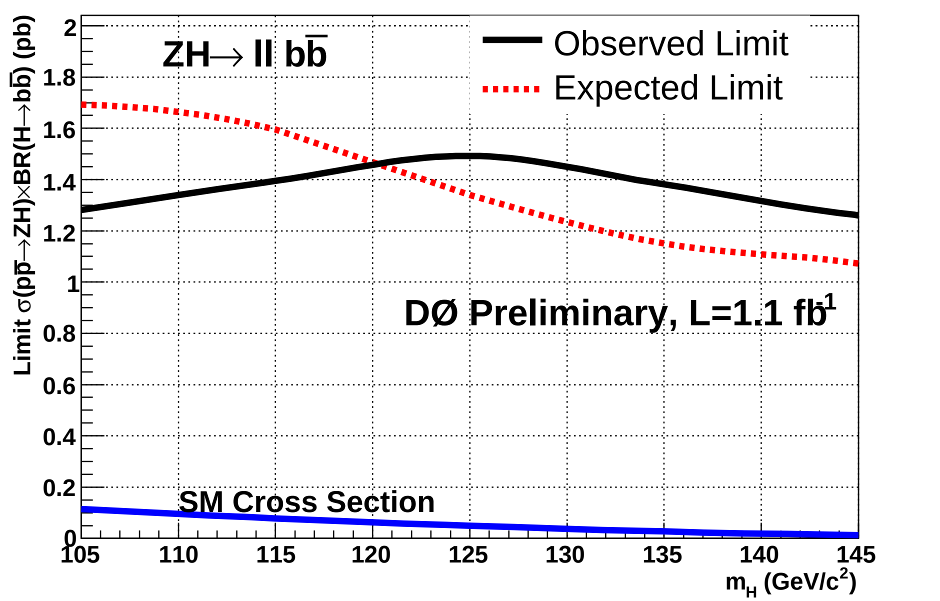
→ NNLO QCD corrections have been calculated for the signal [O.Brien, A.Djouadi and R.Harlander, 2004]

→ $O(\alpha)$ EW corrections have been calculated for the signal [M.L.Ciccolini, S.Dittmaier and M.Kramer, 2003]

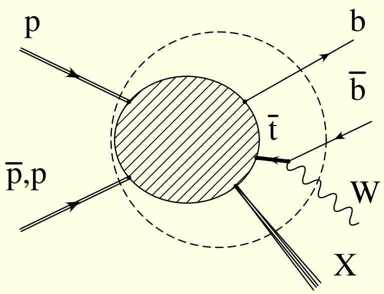
→ Results for WH associated production, August 2007



→ Results for ZH associated production, August 2007



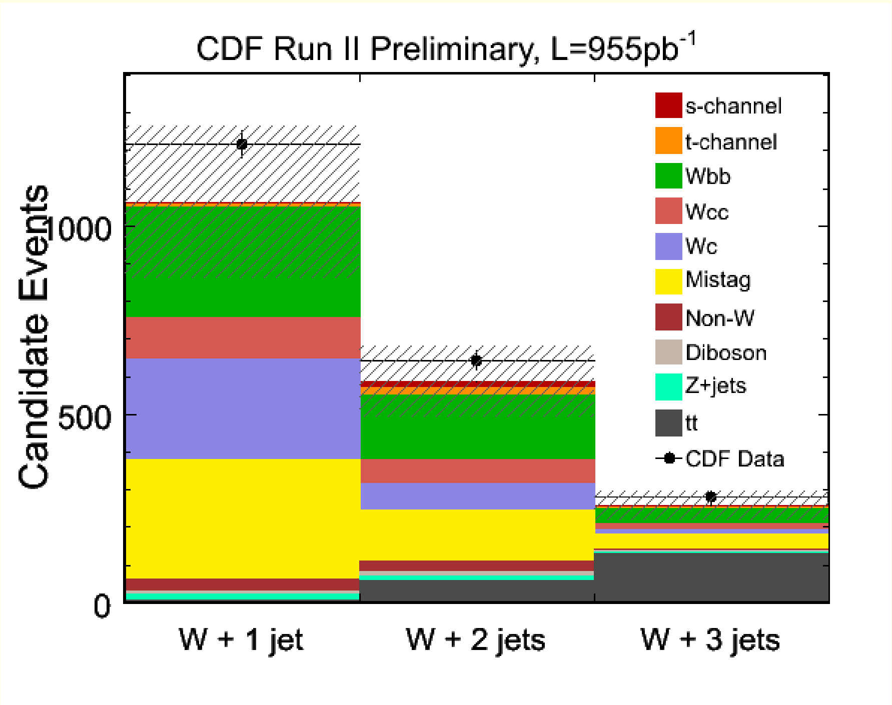
SM Single-Top production



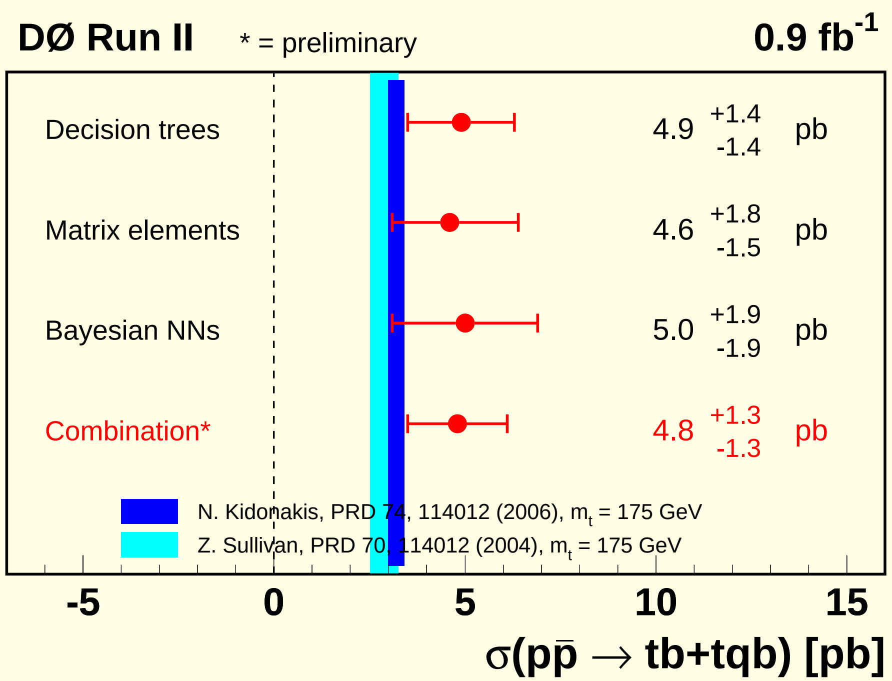
⟶ NLO QCD corrections have been thoroughly studied [T.Stelzer, Z.Sullivan and S.Willenbrock, 1998; B.W.Harris, E.Laenen, L.Phaf, Z.Sullivan and S.Weinzierl, 2002; . . .]

⟶ NLO EW corrections have been calculated for the (SM and MSSM) signal [M.Beccaria, G.Macorini, F.M.Renard and C.Verzegnassi, 2006]

→ CDF data sample, October 2006



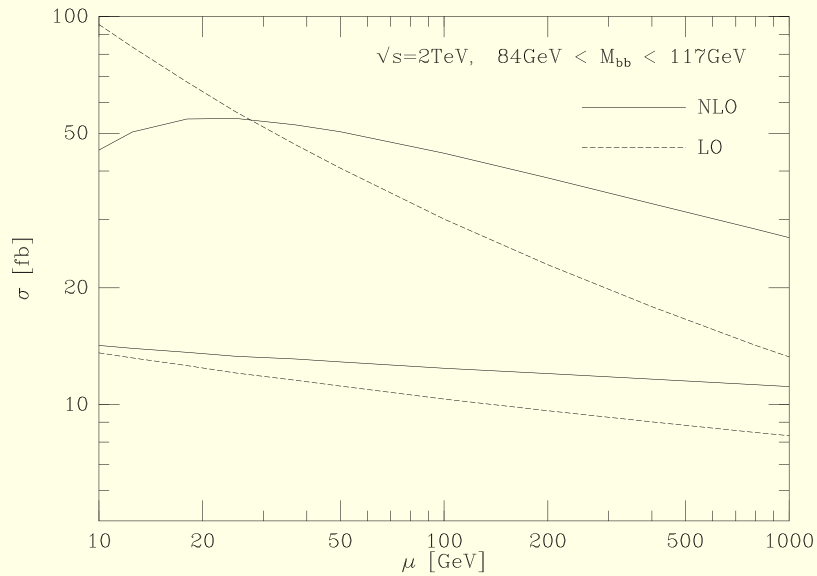
→ $D0$ evidence of single-top, March 2007



The Calculation

$Wb\bar{b}/Zb\bar{b}$ production

- NLO calculation, with $m_b = 0$ approximation available in MCFM [J.Campbell and R.K.Ellis]



[R.K.Ellis and S.Veseli, 1998]

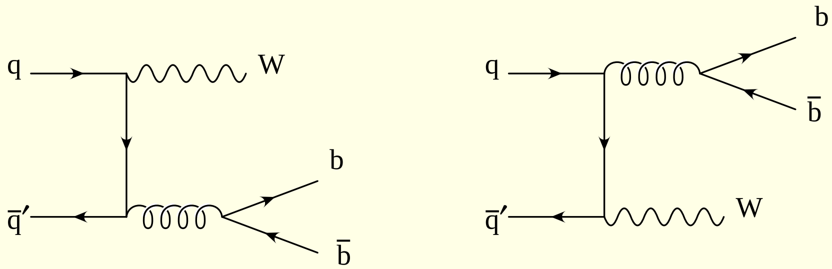
⟶ Kinematical cuts were imposed in the massless approximation in order to simulate mass effects:

$$p^T_{b,\bar{b}} > m_b \quad \text{and} \quad (p_b + p_{\bar{b}})^2 > 4m_b^2 .$$

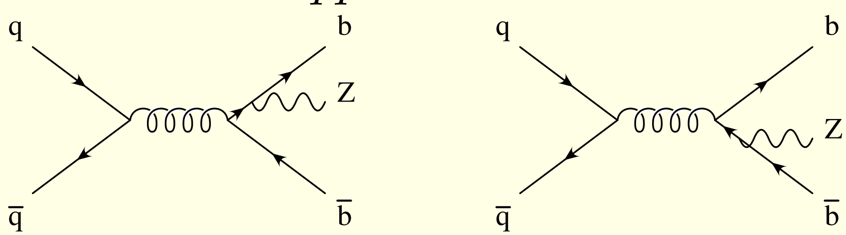
⟶ Error on the differential cross section from $m_b = 0$ approximation expected to be small ($\sim 10\%$ from LO estimates) but relevant, difficult to quantify due to non trivial contribution of m_b coming from phase space and matrix elements.

Calculation with full m_b effects

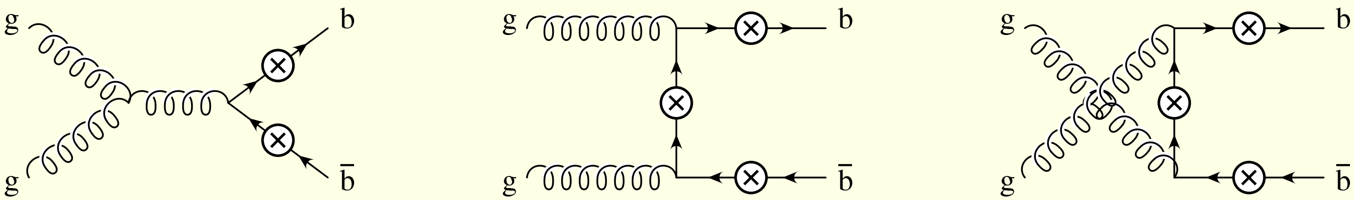
LO Feynman diagrams:



$q\bar{q}' \rightarrow Wb\bar{b}$



$q\bar{q} \rightarrow Zb\bar{b}$



$gg \rightarrow Zb\bar{b}$

Subprocesses at LO:

$\longrightarrow$ $Wb\bar{b}$: $q\bar{q}' \rightarrow Wb\bar{b}$

$\longrightarrow$ $Zb\bar{b}$: $q\bar{q} \rightarrow Zb\bar{b}$ and

$Zb\bar{b}$: $gg \rightarrow Zb\bar{b}$

Including $\mathcal{O}(\alpha_s)$ corrections

$$
\begin{aligned}
\hat{\sigma}_{ij}^{\mathrm{NLO}}(x_1, x_2, \mu) &= \alpha_s^2(\mu) \left\{ f_{ij}^{\mathrm{LO}}(x_1, x_2) + \frac{\alpha_s(\mu)}{4\pi} f_{ij}^{\mathrm{NLO}}(x_1, x_2, \mu) \right\} \\
&\equiv \hat{\sigma}_{ij}^{\mathrm{LO}}(x_1, x_2, \mu) + \delta\hat{\sigma}_{ij}^{\mathrm{NLO}}(x_1, x_2, \mu) \; ,
\end{aligned}
$$

$$
\delta\hat{\sigma}_{ij}^{\mathrm{NLO}} = \hat{\sigma}_{ij}^{\mathrm{virt}} + \hat{\sigma}_{ij}^{\mathrm{real}} \; .
$$

- Virtual Corrections: consist of one-loop diagrams interfered with LO amplitude
  - $Wb\bar{b}$: one subprocess, $q\bar{q}' \to Wb\bar{b}$
  - $Zb\bar{b}$: two subprocesses, $q\bar{q} \to Zb\bar{b}$ and $gg \to Zb\bar{b}$
- Real Corrections: consist of tree level diagrams with one extra parton
  - $Wb\bar{b} + k$: two subprocess, $q\bar{q}' \to Wbb + g$ and $q(\bar{q})g \to Wb\bar{b} + q'(\bar{q}')$
  - $Zb\bar{b} + k$: three subprocesses, $q\bar{q} \to Zb\bar{b} + g$, $gg \to Zb\bar{b} + g$ and $q(\bar{q})g \to Zb\bar{b} + q(\bar{q})$

Virtual corrections: calculating $\hat{\sigma}_{ij}^{\rm virt}$

$$\hat{\sigma}_{ij}^{\rm virt} = \int d\,(PS_3)\,\overline{\sum}|\mathcal{A}_{\rm virt}(ij \to W/Z\ b\bar{b})|^2$$

where:

$$\overline{\sum}|\mathcal{A}_{\rm virt}(ij \to W/Z\ b\bar{b})|^2 = \sum_D \overline{\sum}\left(\mathcal{A}_0\mathcal{A}_D^\dagger + \mathcal{A}_0^\dagger\mathcal{A}_D\right) = \sum_D \overline{\sum} 2\mathcal{R}e\left(\mathcal{A}_0\mathcal{A}_D^\dagger\right)\ .$$

$\longrightarrow$ Use dimensional regularization to regularize UV and IR divergencies.

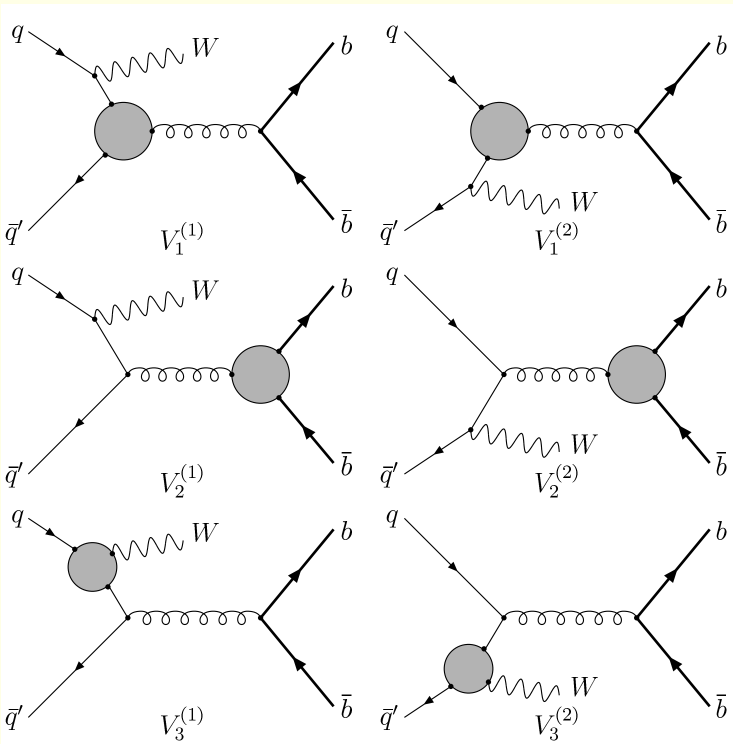
$\longrightarrow$ UV divergencies are canceled by a suitable set of counterterms.

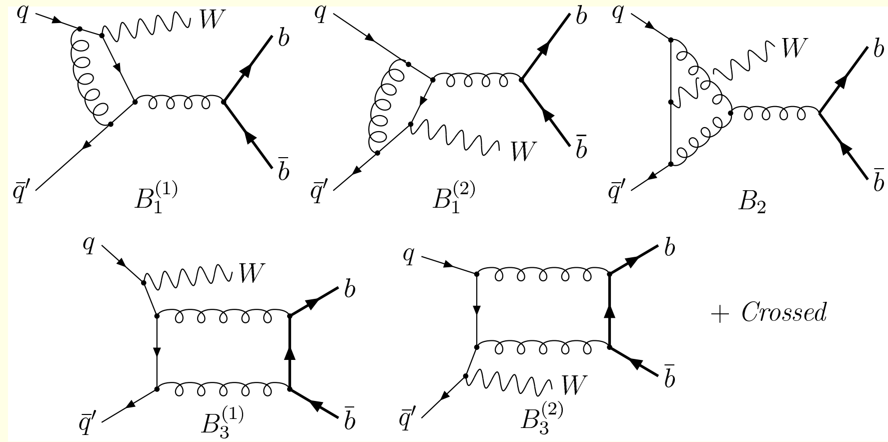
$\longrightarrow$ Calculate each diagram as linear combination of Dirac structures with coefficients that depend on both tensor and scalar integrals.

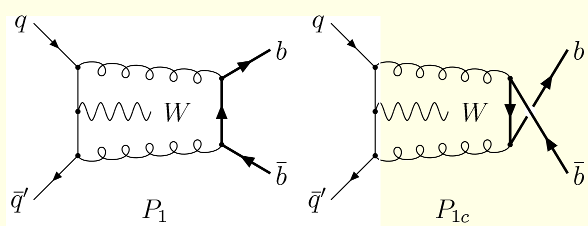
$\longrightarrow$ Tensor integrals reduced analytically to scalar integrals and organized to avoid spurious divergences due to appearance of inverse power of Gram Determinant.

$\longrightarrow$ IR divergencies will cancel with $\hat{\sigma}_{ij}^{\rm real}$.

Virtual corrections: calculating $\hat{\sigma}_{ij}^{\text{virt}}$ - The $Wb\bar{b}$ Diagrams



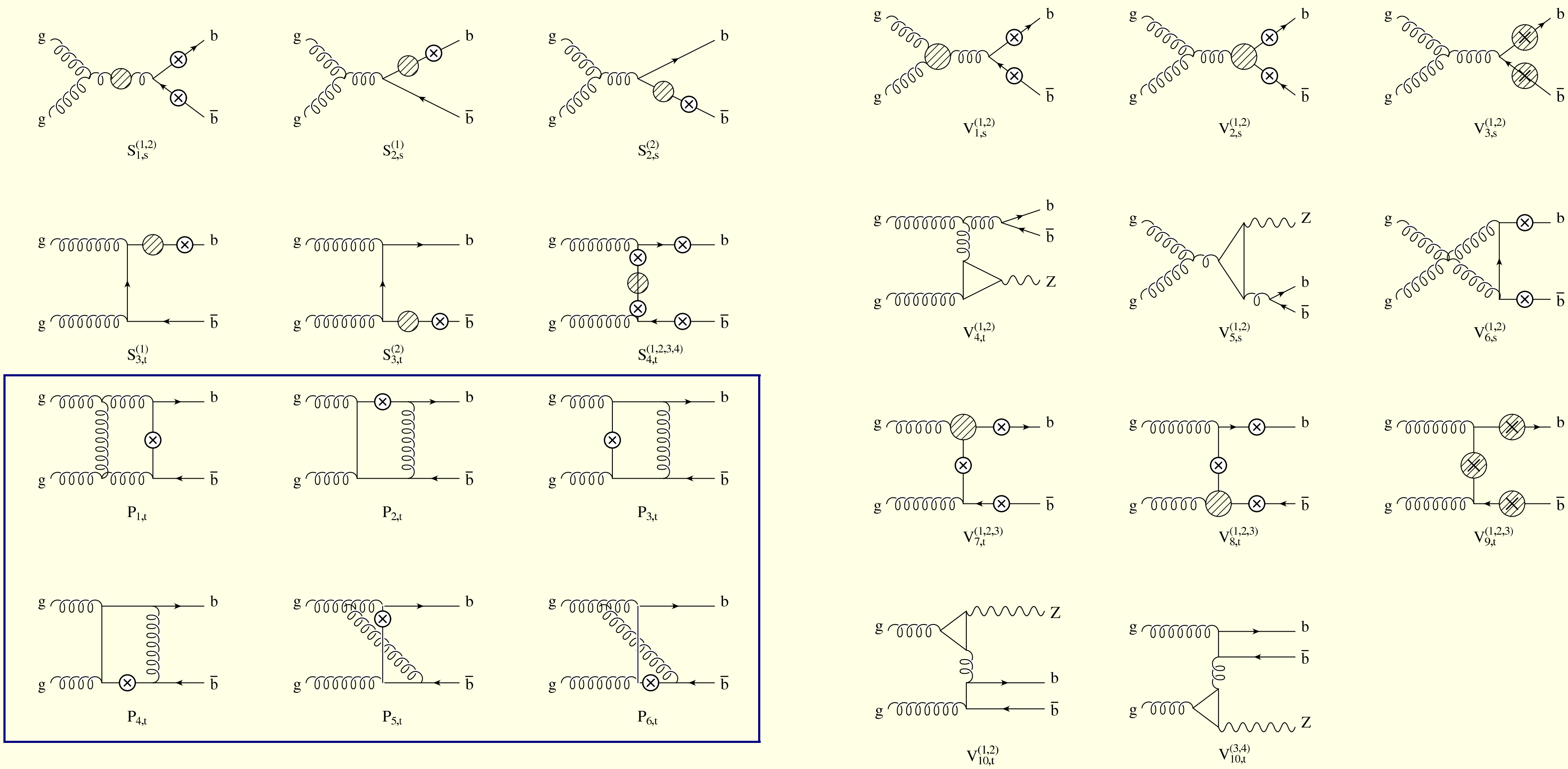




$\longrightarrow$ Counting: 2 diagrams at LO - $\sim$30 at NLO - 2 pentagons

Virtual corrections: calculating $\hat{\sigma}_{ij}^{\text{virt}}$

The $gg \to Zb\bar{b}$ Diagrams



$\longrightarrow$ Counting: 8 diagrams at LO - $\sim$100 at NLO - 12 pentagons

Real corrections: calculating $\hat{\sigma}_{ij}^{\rm real}$

$$\hat{\sigma}_{ij}^{\rm real} \;\; = \;\; \int d\,(PS_4)\,\overline{\sum}|\mathcal{A}_{\rm real}(ij \to W/Z\; b\bar{b} + k)|^2$$

$\longrightarrow$ IR divergencies associated with the integration over the PS of the extra parton, can be extracted using the so called Phase Space Slicing (PSS) method with *two cutoffs*.

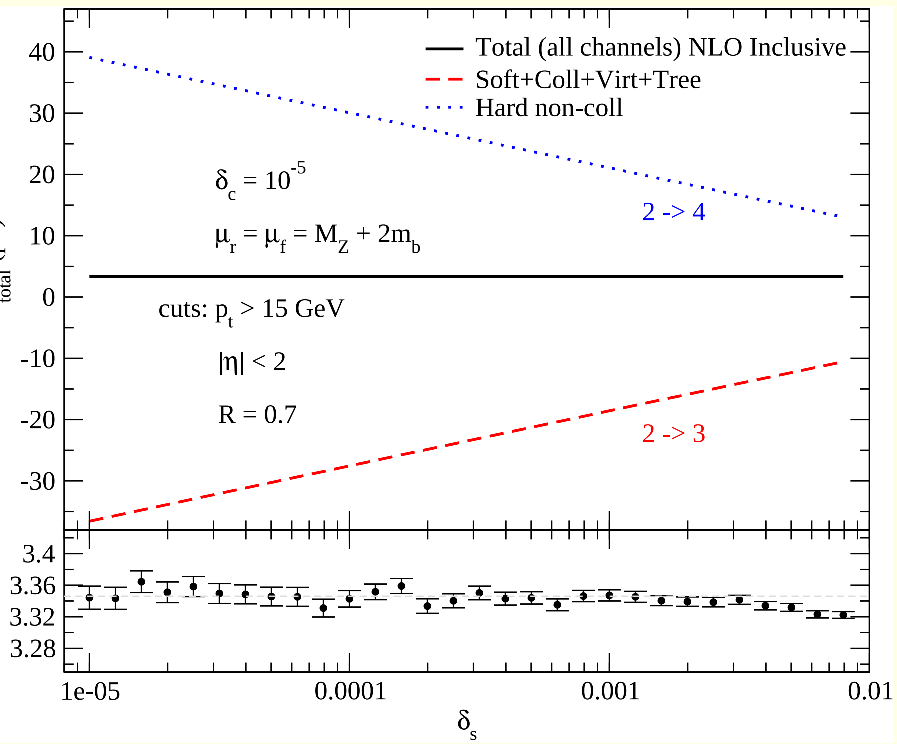
$\longrightarrow$ PSS with two cutoffs uses two unphysical parameters, δ_s and δ_c to isolate soft and collinear divergent regions, where IR singularities are extracted analytically.

$\longrightarrow$ Same soft/collinear structure as $Ht\bar{t}/Hb\bar{b}$, tested against one-cutoff PSS and dipole subtraction method.

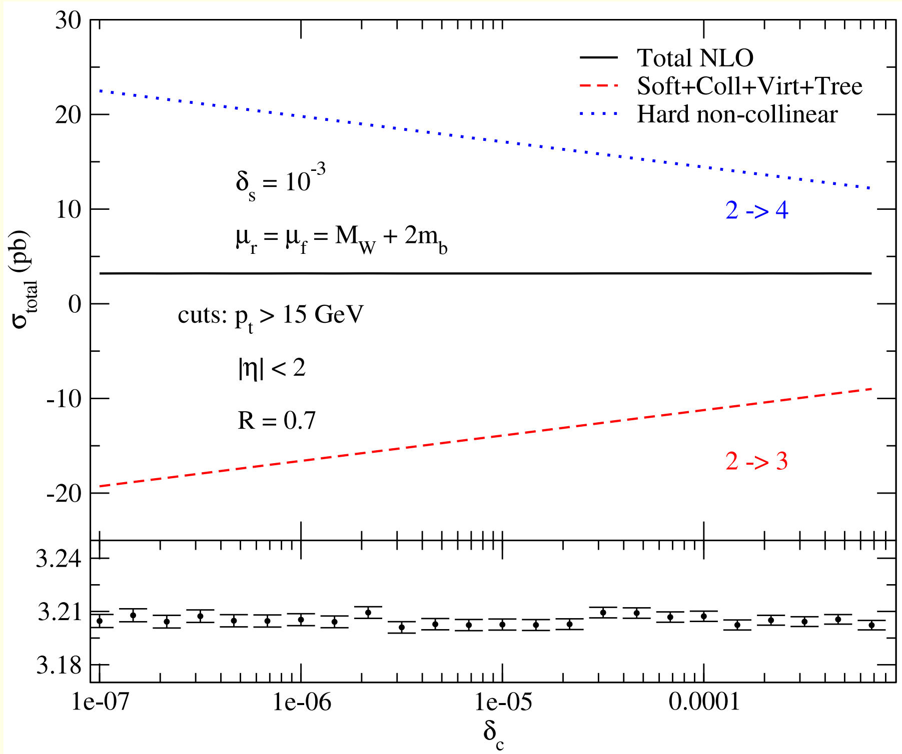
$\longrightarrow$ Physical quantities are independent of δ_s and δ_c, for small enough values of these parameters.

Real corrections: calculating $\hat{\sigma}_{ij}^{\mathrm{real}}$

Independence of the total cross section of δ_s and δ_c cuts



δ_s run for the $Zb\bar{b}$ total cross section



δ_c run for the $Wb\bar{b}$ total cross section

$\longrightarrow$ In the following we will fix $\delta_s = 10^{-3}$ and $\delta_c = 10^{-5}$

Numerical Results, Tevatron

General Setup

$\longrightarrow$ For the Wqq' vertex we take the following CKM matrix elements: $V_{ud} = V_{cs} = 0.975$ and $V_{us} = V_{cd} = 0.222$, while we neglect contribution of the third generation (suppressed by corresponding PDFs or CKM matrix elements).

$\longrightarrow$ PDF: for LO results we use 1-loop evolution of α_s and CTEQ6L1, while for NLO results 2-loop evolution of α_s and CTEQ6M.

$\longrightarrow$ Mass Values: we use for the weak bosons $M_Z = 91.1876$ GeV and $M_W = 81.410$ GeV, a fixed bottom-quark mass $m_b = 4.62$ GeV and fixed top-quark mass $m_t = 170.9$ GeV (entering through virtual corrections).

b-jet identification

⟶ We use the k_T jet algorithm with $R = 0.7$ and study two cases:

- → Inclusive Cross Section: events with two $(b + \bar{b})$ or three $(b + \bar{b} + j)$ jets resolved contribute to the cross section.
- → Exclusive Cross Section: only events with two $(b + \bar{b})$ jets resolved contribute to the cross section.

Same convention used by MCFM (used to obtain the results for $m_b = 0$).

⟶ b-jet kinematical cuts:

- → Transverse momentum of the b-jets: $p_t > p_{t,\ min}$ (15 GeV) for both b and $\bar{b}$ jets.
- → Pseudorapidity: $|\eta| < \eta_{max}$ (2) for both b and $\bar{b}$ jets.

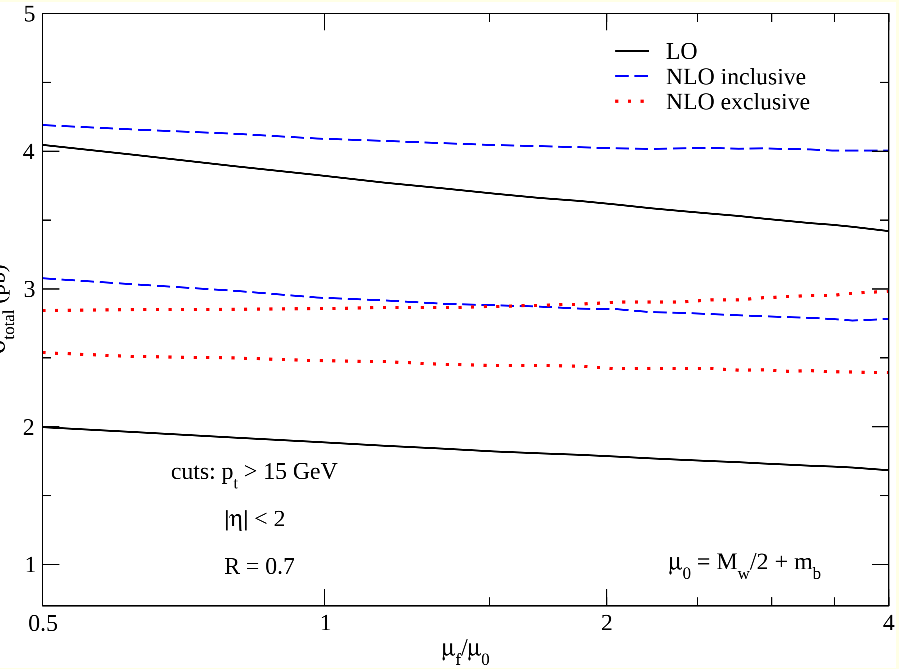
Summary of LO and NLO total cross sections

massive and massless calculation, setting $\mu_r = \mu_f = M_V + 2m_b$ $(V = W, Z)$.

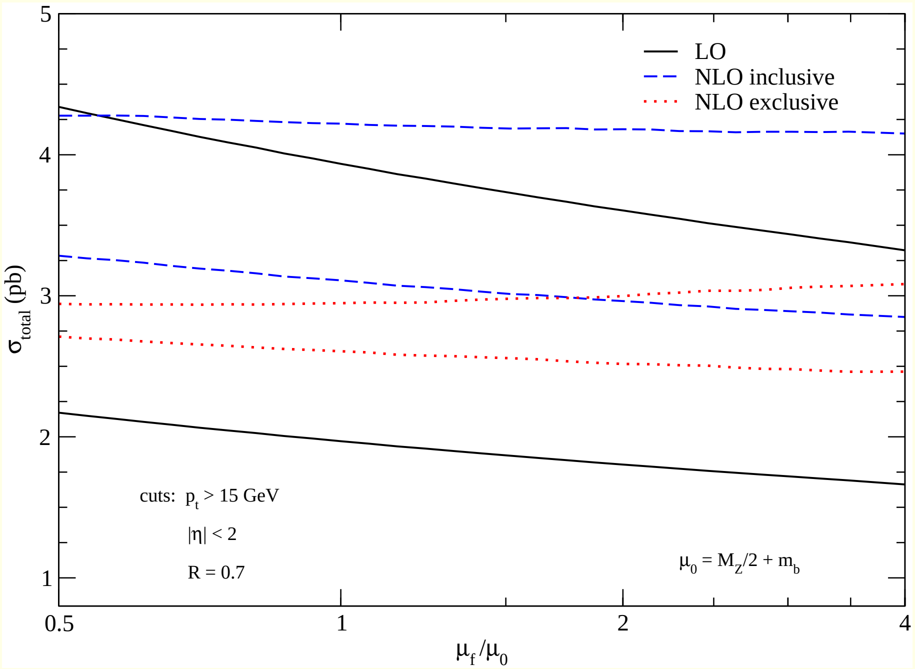
Cross Section, $Wb\bar{b}$	$m_b \neq 0$ (pb) [ratio]	$m_b = 0$ (pb) [ratio]
$\sigma^{\rm LO}$	2.20[-]	2.38[-]
$\sigma^{\rm NLO}$ inclusive	3.20[1.45]	3.45[1.45]
$\sigma^{\rm NLO}$ exclusive	2.64[1.2]	2.84[1.2]

Cross Section, $Zb\bar{b}$	$m_b \neq 0$ (pb) [ratio]	$m_b = 0$ (pb) [ratio]
$\sigma^{\rm LO}$	2.21[-]	2.37[-]
$\sigma^{\rm NLO}$ inclusive	3.34[1.51]	3.64[1.54]
$\sigma^{\rm NLO}$ exclusive	2.75[1.24]	3.01[1.27]

Scale dependence and theoretical uncertainty



$Wb\bar{b}$: PRD 74 (2006) 034007

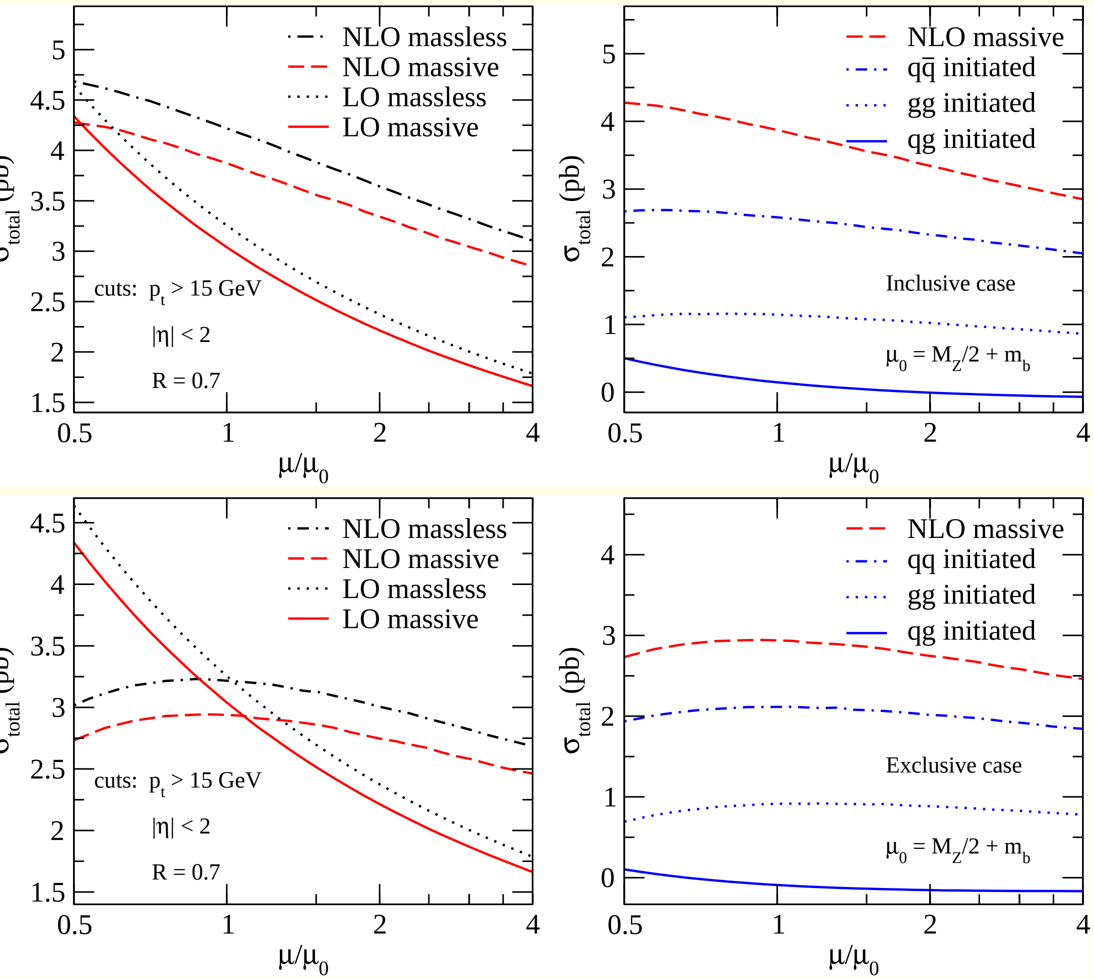


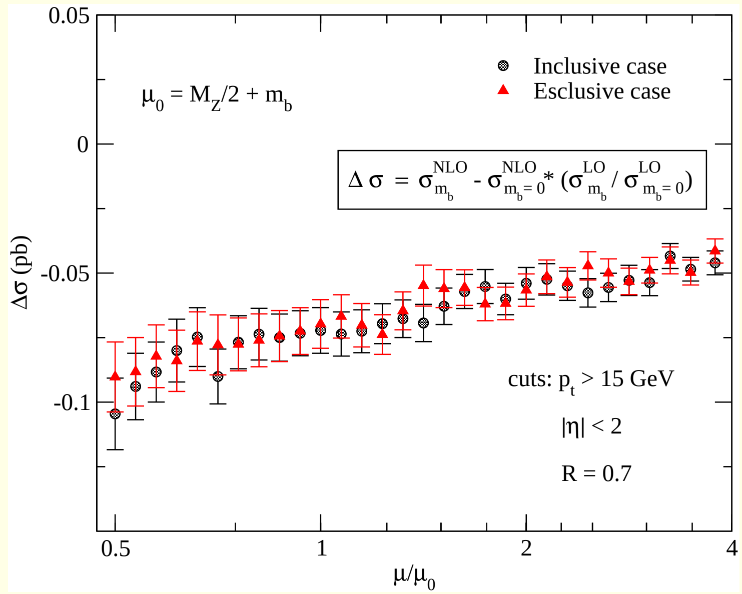
$Zb\bar{b}$: PRELIMINARY

$\longrightarrow$ Bands obtained by varying both μ_R and μ_F between $\mu_0/2$ and $4\mu_0$ (with $\mu_0 = m_b + M_V/2$ ($V = W, Z$)).

- LO uncertainty $\sim 40\%$.
- Inclusive NLO uncertainty $\sim 20\%$.
- Exclusive NLO uncertainty $\sim 10\%$.

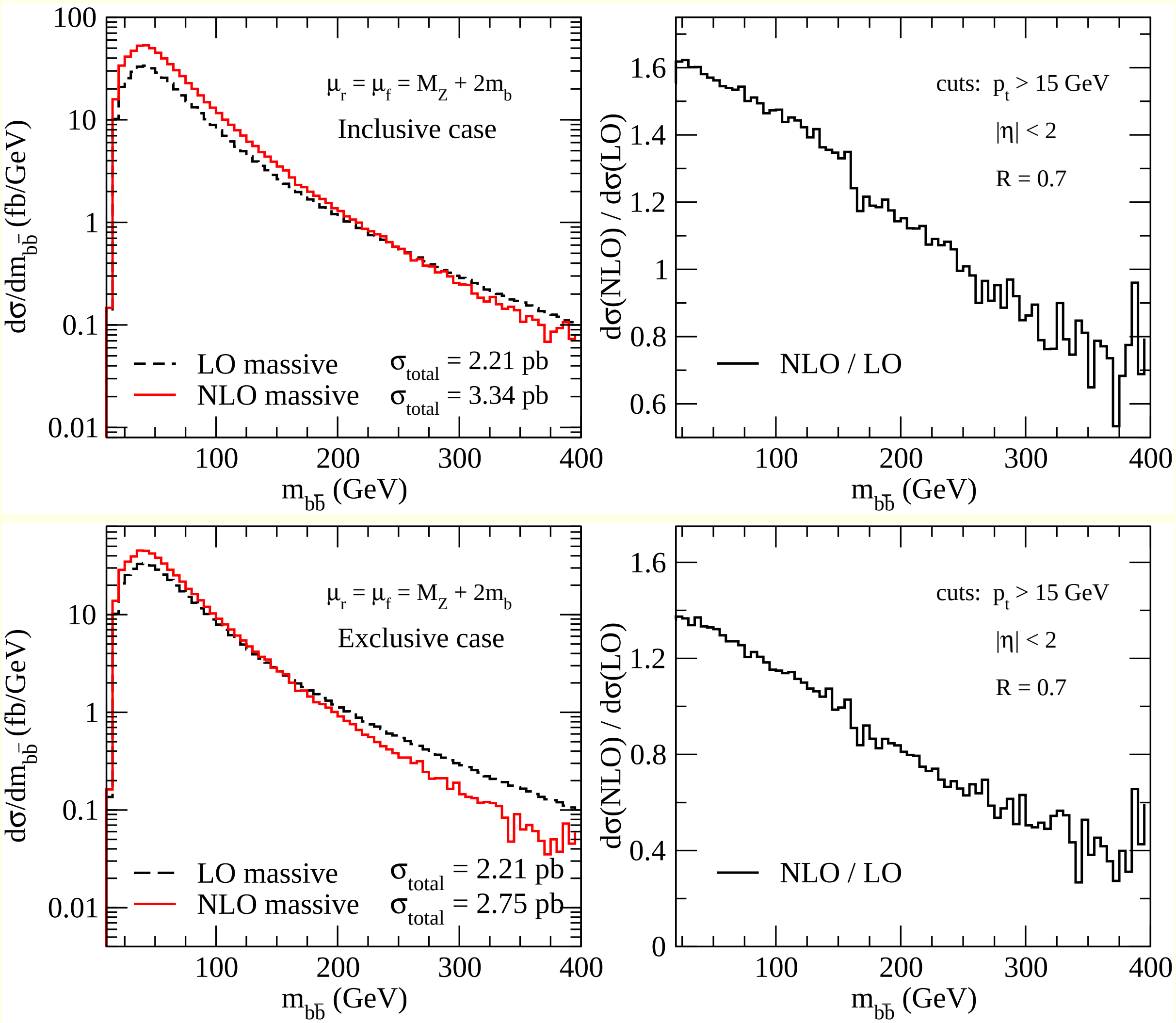
$Zb\bar{b}$, scale dependence: LO vs NLO and massless vs massive





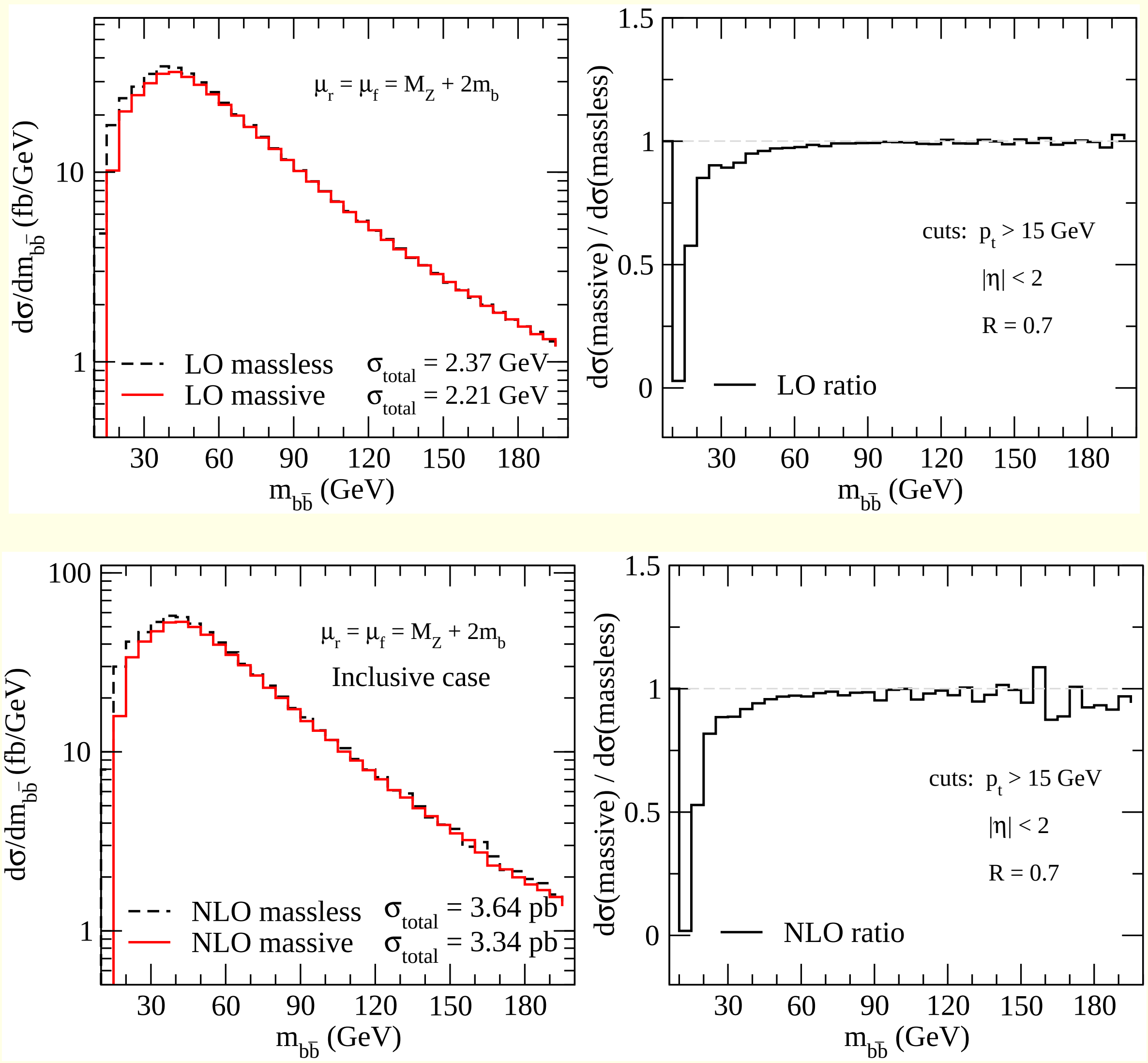
PRELIMINARY

$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, LO vs NLO



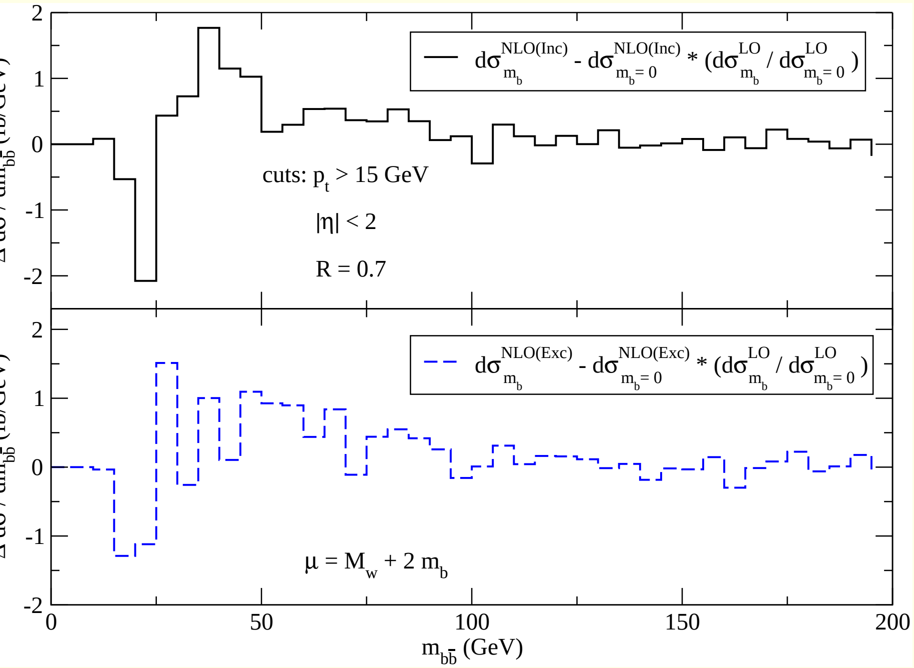
PRELIMINARY

$Zb\bar{b}$: $m_{b\bar{b}}$ distributions, massive vs massless

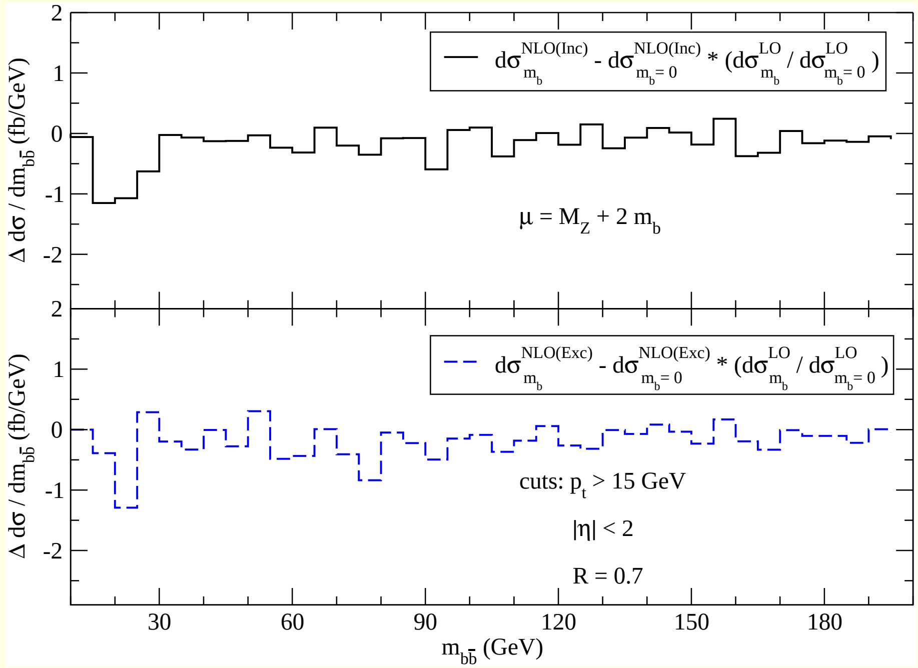


PRELIMINARY

$Wb\bar{b}/Zb\bar{b}$, $m_{b\bar{b}}$ distributions: testing rescaling



$Wb\bar{b}$: PRD 74 (2006) 034007



$Zb\bar{b}$: PRELIMINARY

Not accurate in the low $m_{b\bar{b}}$ invariant mass region.

Summary

- We have calculated the NLO QCD corrections to $Wb\bar{b}/Zb\bar{b}$ production at hadron colliders including full bottom-quark mass effects.
- We observe considerable reduction of the theoretical uncertainty in the total cross section with respect to the LO calculation. Specifically the 40% LO uncertainty is reduced to 20% for inclusive NLO production and to 10% for exclusive NLO production for both $Wb\bar{b}$ and $Zb\bar{b}$.
- Mass effects reduce by 8% to 10% the total cross section, affecting in particular the low invariant mass region of the $b\bar{b}$ pair.
- Our results are of relevance to the search for a SM-like Higgs particle in the VH ($V = W, Z$) associated production channel and to the measurement of single-top production, both processes of great interest to the high energy community.

Outlook

- We will keep studying the phenomenological impact of our calculation.
- We are currently studying the impact of our calculation on searches for single-top production, where we also consider final states with less than two b-quarks (with J. Campbell, F. Maltoni, S. Willenbrock).
- We will implement our calculation for the LHC case. Since at the LHC gluon initiated processes are enhanced, we expect some fundamental differences to appear.
- Our calculation can be naturally extended to other important processes like $Zt\bar{t}$, $\gamma t\bar{t}$ and $\gamma b\bar{b}$ production.